CHANNEL CHANGES IN THE COLORADO RIVER BELOW GLEN CANYON DAM

By: Ernest L. Pemberton, Hydraulic Engineer, U.S. Bureau of Reclamation, E&R Center, Denver, Colorado

ABSTRACT

Construction of Glen Canyon Dam on the Colorado River by the Bureau of Reclamation started in 1956, and the dam was officially closed in March 1963. The 1957 degradation study based on a detailed bottom sediment sampling program in 1956 and an analytical approach to sediment transport and armor resulted in a prediction of about a 1.22-meter (4-foot) degradation immediately below the dam and 8.26 million cubic meters (6,700 acre-feet) of erosion to take place in the reach above the mouth of the Paria River in about 14 years.

To verify changes since closure of the dam, resurveys of cross sections in the approximate 24-kilometer (15-mile) reach of the Colorado River from Glen Canyon Dam to the mouth of the Paria River near Lees Ferry were made in 1959, 1963, 1965, and 1975. Bottom sediment samples were also collected in 1966 and 1975 to analyze the changes in material size as a result of the degradation and armoring process. The resurveys confirmed the 1957 predictive study by noting that sufficient armoring material remained to control excessive degradation with about 9.87 million cubic meters (8,000 acre-feet) of material scoured from the channel bottom by 1975. This paper summarizes the 1957 predictive study of probable degradation and describes the changes that have taken place in the channel from 1956 to 1975.

INTRODUCTION

In the design of Glen Canyon Dam, engineers recognized that sediment carried by the Colorado River would be trapped in Lake Powell with an estimated annual sediment inflow to the reservoir averaging about 128 million cubic meters (104,000 acre-feet) (Gessel, 1963). With sediment being deposited in the reservoir, releases through the powerplant or spills through the spillway would be clear water capable of degrading the channel downstream from the dam. A 1956 field study encountered problems in collecting adequate field data on channel hydraulics and river bottom sediments needed to predict downstream channel changes. Development of analytical procedures on sediment transport and armoring material proved equally as difficult as application of engineering judgment to formulate conclusions and quantify downstream channel degradation. The degradation and tailwater studies completed in 1957 served as a basis for final design of the powerplant, outlet works, and spillway outlet for Glen Canyon Dam.

Resurveys of river ranges below Glen Canyon Dam have provided information for quantifying the degradation occurring since 1963. Samples of river bottom sediment and especially the armoring materials provided information on the phenomena of armoring that can occur below such a structure. Surveys of river ranges and sediment sampling were conducted in cooperation with the Upper Colorado Regional Office of the Bureau of Reclamation in Salt Lake City, Utah.

1957 DEGRADATION STUDY

Anticipating the channel would degrade below the dam, a detailed channel hydraulic and sediment sampling program was undertaken in 1956 (Miller and Borland, 1957).

The purpose of collecting field data on the stream bottom sediments was to provide information on the downstream sediments for use in analytical studies on degradation. As a part of the investigations, observations were also made in 1956 on various hydraulic and riverbed conditions that would aid in controlling degradation. This involved locating the exposed gravel or cobble bars and determining the depth to underlying gravel bars or rock controls. Twenty-four river cross sections (figure 1) were also surveyed for use in water surface profile computations. In 1956, 10 downstream ranges (figure 2) were selected for resurvey after the dam was constructed to monitor any downstream changes.

The detailed sediment sampling accomplished in 1956 consisted of three types of samples.

1. Bottom sediment samples of channel bed surface.

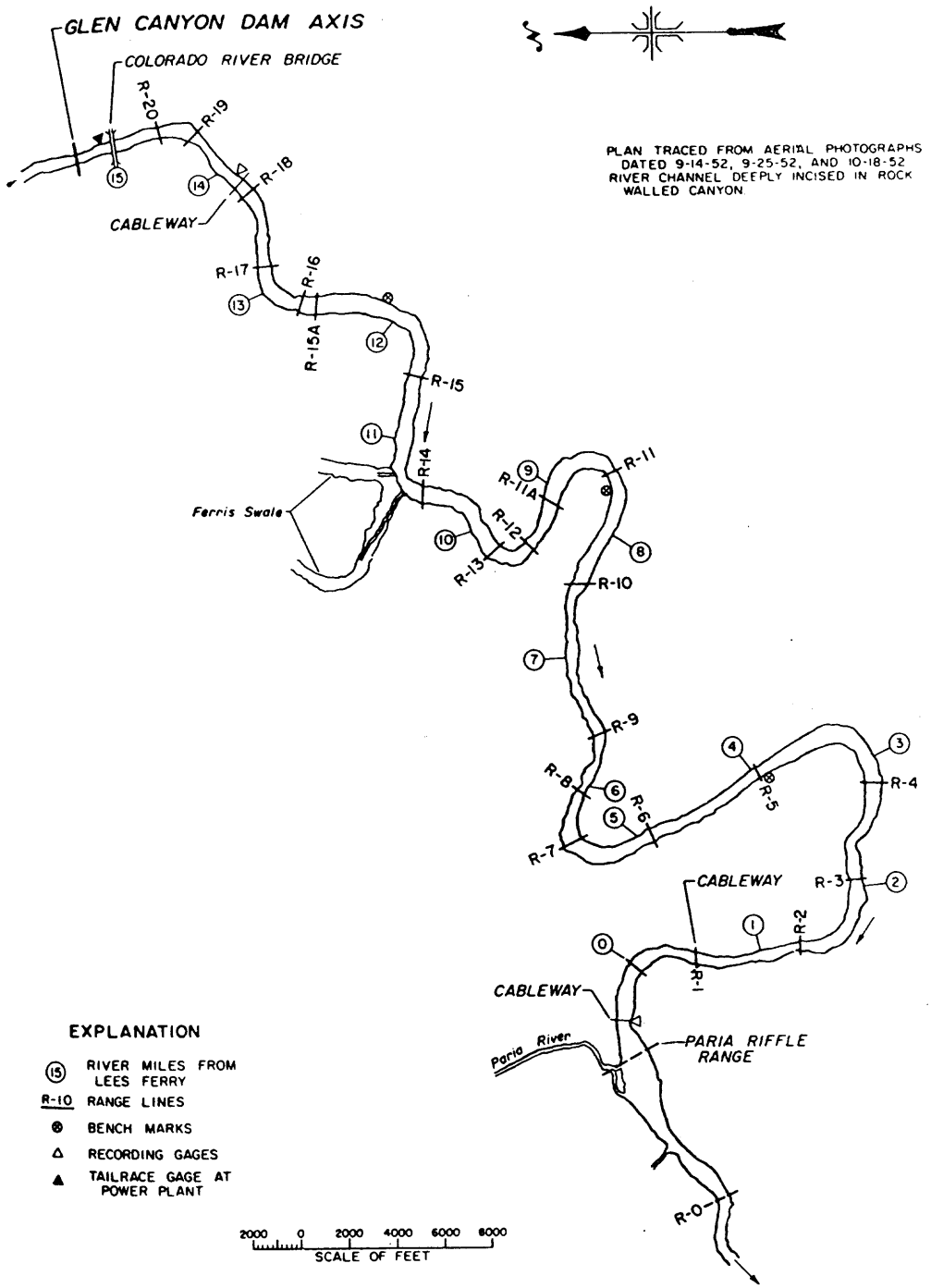
2. Ten deep bottom sediment samples penetrating to about 7.6 meters (25 feet) were collected between the damsite and Lees Ferry (figure 3).

3. A jet probe was devised to penetrate through the sand-size material overlying streambed gravel bars and deposits at nine locations randomly selected within the 24-kilometer (15-mile) reach above Lees Ferry. The jet probe was unable to penetrate the underlying gravels thought to consist of large gravels, cobbles, or possibly bedrock.

Observations of stream channel conditions influencing degradation indicated that a gravel bar existed below range 15 located about 5.6 kilometers (3-1/2 miles) below Glen Canyon Dam and a bar of gravel and cobble-size material was located at the riffle near the mouth of the Paria River. The bars consisted of rounded, stream-worn, hard rocks varying in size from 4 millimeters to over 203 millimeters (8 inches) in diameter and where exposed (e.g., range 15), they were shingled and well compacted.

The average size analyses for the various channel bottom samples collected in 1956 are shown in figure 4. The mean size (D_{50}) of the surface bottom sediments was 0.21 millimeter, of the sands overlying gravels was 0.32 millimeter, and of the underlying gravels was 20 millimeters. Sediment transport studies for evaluating the degradation below Glen Canyon Dam were made by use of the bedload equations (e.g., Schoklitsch, Haywood, and Meyer-Peter, Muller) and with the anticipated powerplant releases averaging about 382 cubic meters per second (13,500 cubic feet per second). These bedload transport equations indicated that about 617,000 cubic meters (500 acre-feet) of sand-size sediment per year would be scoured from the Colorado River between Glen Canyon Dam and Lees Ferry. A transportable size analysis with varying discharges up to flood flows, indicated sufficient gravels in the size range from 50 millimeters to 203 millimeters (2 to 8 inches) underlying the sands

equations based on average powerplant release, not effective or peak discharge.

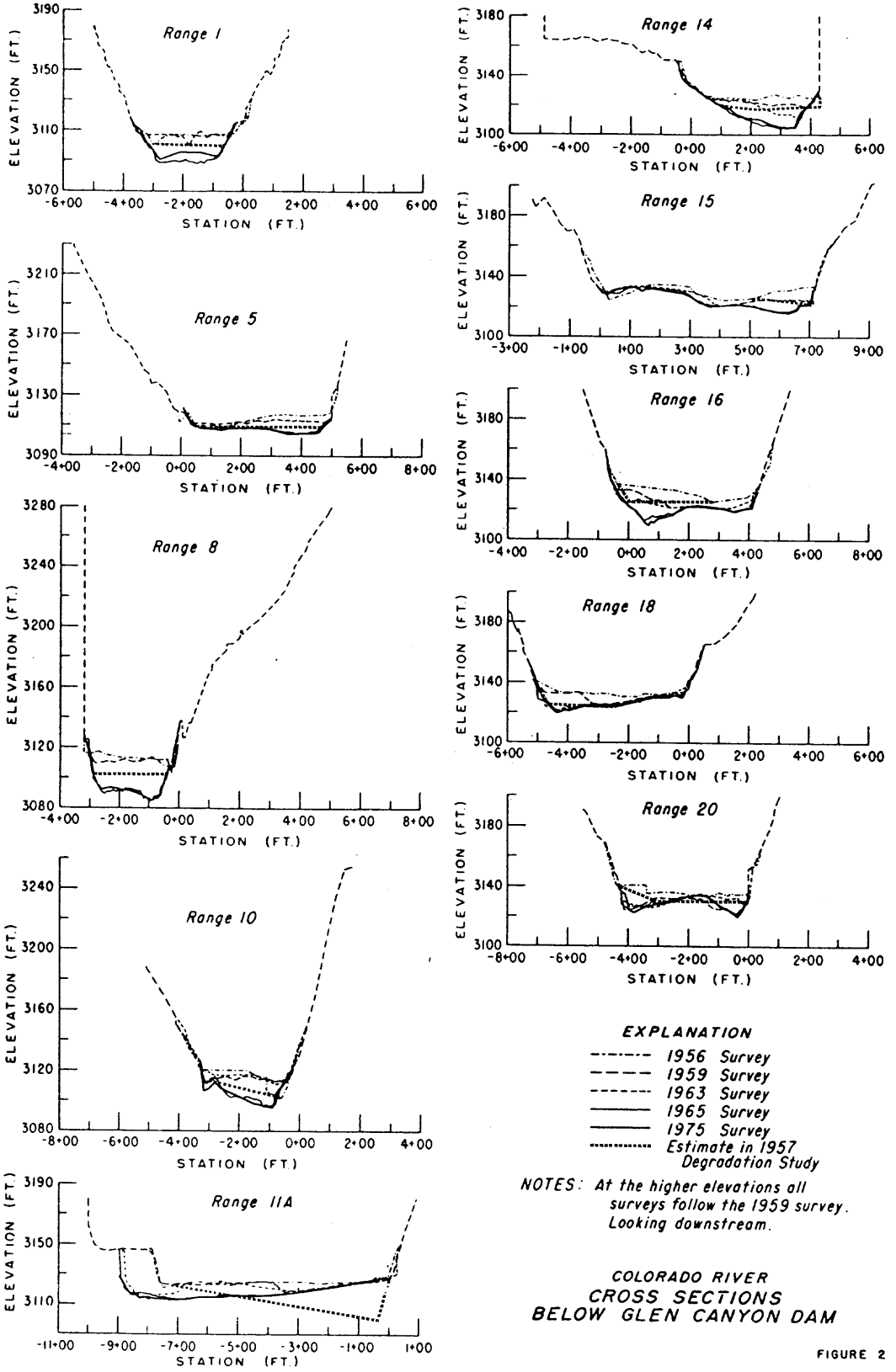


COLORADO RIVER - ARIZONA

LEES FERRY TO GLEN CANYON DAM AXIS

LOCATION MAP

FIGURE 1



COLORADO RIVER
CROSS SECTIONS
BELOW GLEN CANYON DAM

FIGURE 2

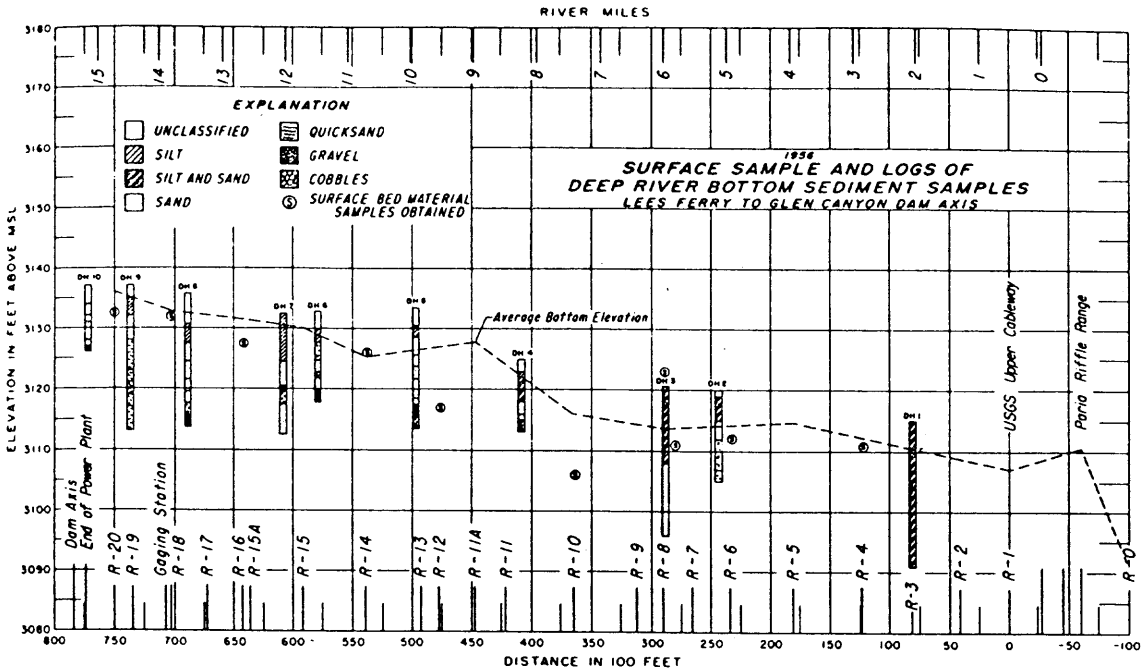


FIGURE 3

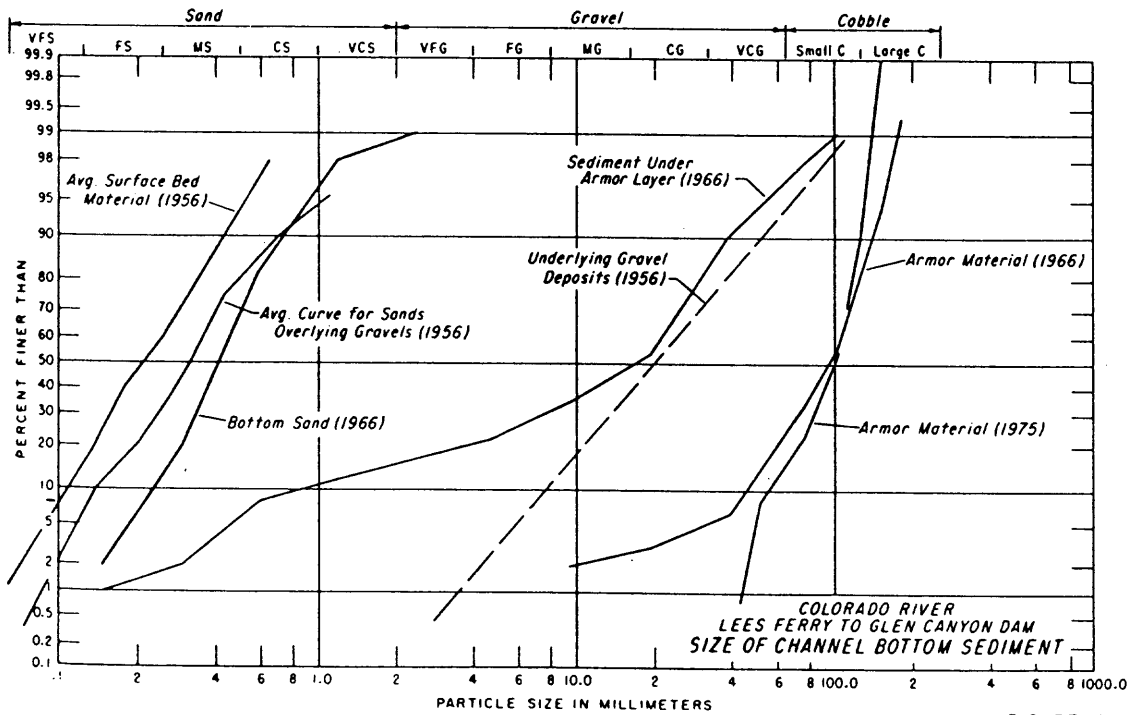


FIGURE 4

to provide stability. Based on the analytical approach for transport, armoring and engineering judgment, the degradation study (Miller and Borland, 1957) concluded that only the sand materials overlying the gravels would be degraded. The volume of this sand-size material that would be degraded was estimated to be about 8.26 million cubic meters (6,700 acre-feet) which for average powerplant releases would take place in about 14 years. Degradation immediately below the dam as limited by armoring would be about 1.22 meters (4 feet).

RESURVEYS AND OBSERVATIONS DURING CONSTRUCTION 1959 - 1963

In July 1959 changes in tailwater in the reach downstream from Glen Canyon Dam construction area were observed. These changes consisted of a 1.2-meter (4-foot) drop in water surface elevation near range 20. A plot of the maximum monthly mean daily peak-flow hydrograph (figure 5) shows that much higher flows occurred during 1959 than the anticipated powerplant releases of about 382 cubic meters per second (13,500 cubic feet per second). Degradation in 1959 was undoubtedly caused by both the high riverflows and the deposition of sediment in the storage area upstream from the cofferdam with about 130 million cubic meters (105,000 acre-feet) of storage.

The 1959 resurveys of the ranges selected for monitoring purposes showed a maximum lowering in mean streambed elevation at range 20 of 1.83 meters (6 feet) since the 1956 survey. A comparison of the 1956 with 1959 surveys showed that 2.17 million cubic meters (1,760 acre-feet) of sediment had been scoured from the Colorado River channel in the 9.7 kilometers (6 miles) below Glen Canyon Dam. There was very little degradation in the remaining 22.5 kilometers (14 miles) above Lees Ferry. Early in 1960, observations of the downstream channel showed that the scouring had also uncovered gravel and cobble bars that were retarding any further scour in most areas and were already becoming quite stable.

To further monitor the apparently high rates of degradation that were taking place during construction, another survey of the downstream ranges was made in 1963 in the reach upstream from range 10. The volume of material degraded from the channel bottom in the 3.55-year period from 1959 to 1963 was 1.52 million cubic meters (1,230 acre-feet) in the reach above range 10. The deposition of sediment above the upstream cofferdam combined with the high relatively clear discharges below the dam between 1959 and 1963 scoured sediment from the reach above range 10 and left a series of controls in the riverbed that were well armored with gravel and cobble-size materials.

1965 AND 1975 RESURVEYS

The complete set of ranges was resurveyed in 1965 with 7.57 million cubic meters (6,140 acre-feet) of sands scoured from the river bottom in the 5.8-year period from 1959 to 1965. This survey was the first since closure of the dam in March of 1963. The high peak release of 1,645 cubic meters per second (58,100 cubic feet per second) in May of 1965 is depicted on figure 6 with a photograph of the dam taken in 1965. This type of release created some deep holes that continued to degrade the downstream channel.

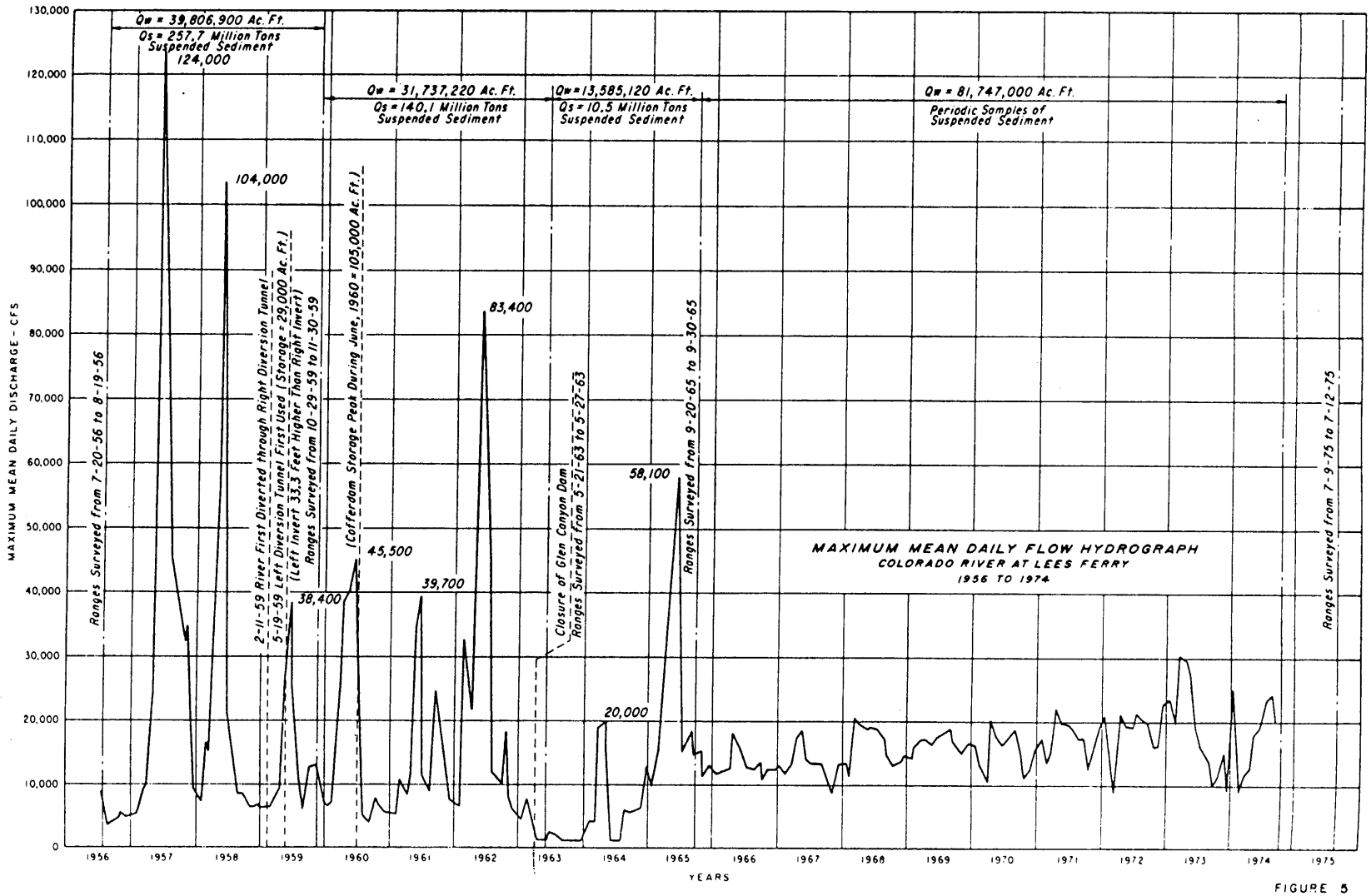

Qw = 39,806,900 Ac. Ft.
Qs = 257.7 Million Tons Suspended Sediment
Qw = 31,737,220 Ac. Ft.
Qs = 140.1 Million Tons Suspended Sediment
Qw = 13,585,120 Ac. Ft.
Qs = 10.5 Million Tons Suspended Sediment
Qw = 81,747,000 Ac. Ft.
Periodic Samples of Suspended Sediment
124,000
104,000
83,400
58,100
45,500
39,700
38,400
20,000
Ranges Surveyed from 7-20-56 to 8-19-56
2-11-59 River First Diverted through Right Diversion Tunnel
5-19-59 Left Diversion Tunnel First Used (Storage = 29,000 Ac. Ft.)
(Left Invert 33.3 Feet Higher Than Right Invert)
Ranges Surveyed from 10-29-59 to 11-30-59
(Cofferdam Storage Peak During June, 1960 = 105,000 Ac. Ft.)
Closure of Glen Canyon Dam
Ranges Surveyed from 5-21-63 to 5-27-63
Ranges Surveyed from 9-20-65 to 9-30-65
Ranges Surveyed from 7-9-75 to 7-12-75
MAXIMUM MEAN DAILY FLOW HYDROGRAPH
COLORADO RIVER AT LEES FERRY
1956 TO 1974
MAXIMUM MEAN DAILY DISCHARGE - CFS
YEARS
130,000
120,000
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975

FIGURE 5

Figure 6 - Releases below Glen Canyon Dam on Colorado River in May 1965.

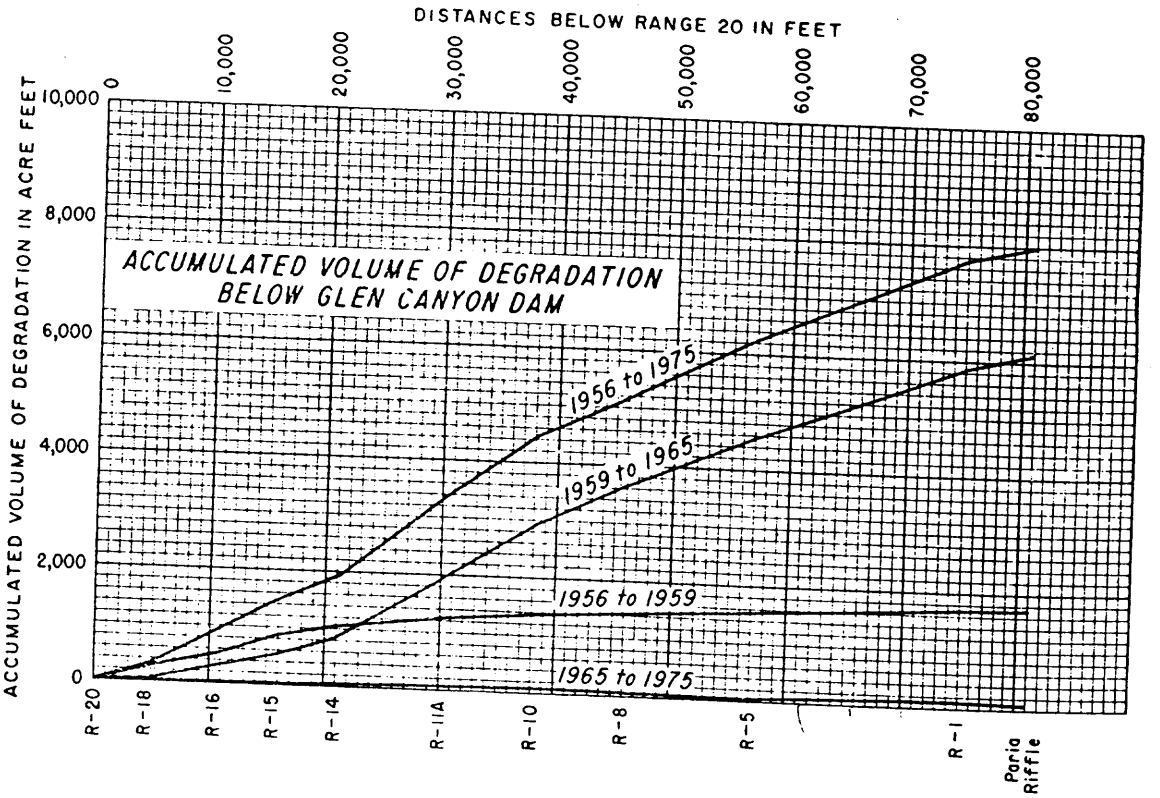


FIGURE 7

Degradation from 1963 to 1965 had now moved downstream from range 15 and was much greater in the lower 14-1/2 kilometers (9 miles) of the river immediately above Lees Ferry.

The resurvey of ranges in 1975, when compared to ranges surveyed in 1965, showed no significant degradation with only about 120,000 cubic meters (97 acre-feet) of material scoured from the river bottom in the 9.8-year period. The accumulated volumes of sediment degraded from the Colorado River channel above Lees Ferry between selected resurveys is shown in figure 7.

SAMPLES OF BOTTOM SEDIMENTS TAKEN IN 1966 AND 1975

In the 1966 observation and sampling program, three major controls (similar to that at range 20 (figure 8)) and six minor controls in the stream bottom were found where the armoring-size material had provided a positive control. The average-size analysis for the armoring materials from samples collected in 1966 is shown on figure 4 with a D_{50} of about 100 millimeters (4 inches). Observations made during the 1966 sampling indicate that the armoring layer was probably about 1 diameter in thickness, but underlying this layer was a mixture of about 20 percent sand, 75 percent gravel, and 5 percent cobbles up to 203 millimeters (8 inches). Most of the sand deposits overlying the gravels that were identified in the 1956 jet probing had been removed leaving an armoring layer of gravels and cobbles at nine locations controlling further degradation. There was still some evidence of medium to coarse sand-size material on the channel bottom above the gravel and cobble controls. The sands were more predominant in the lower reaches above the Paria Riffle.

Observations of channel conditions in July 1975 supported those made in 1966 with about 10 gravel and cobble bars providing positive streambed control similar to that shown in figure 9. At least eight of these controls were located in the upper 13 kilometers (8 miles). The bottom between the controls is predominantly gravel with very little sand. Some sandbanks were noted, but these are being held in check by an increase in vegetative growth. In the upstream reach there is considerable algae growth on both gravels and cobbles. In the downstream reach between controls there was more sand on the bottom and at range 1, the surveyed cross section showed a local sandbar to be moving with a D_{50} of about 0.37 millimeter.

Photographs of the typical armor layer found in 1975 are shown on figures 10 and 11 which were taken near range 20. The size of the armor layer with a D_{50} of 100 millimeters (4 inches) is shown on figure 4 and was almost identieal to that found in 1966.

ARMORING ANALYSIS

The standard Bureau of Reclamation procedures used to evaluate the armoring material size (Strand, 1973) were applied to the reach below Glen Canyon Dam. In addition to the Competent Bottom Velocity, Meyer-Peter, Muller, and Schoklitsch equations used to determine the nontransportable beginning or zero transportable material to define an armoring size, the armoring analysis,

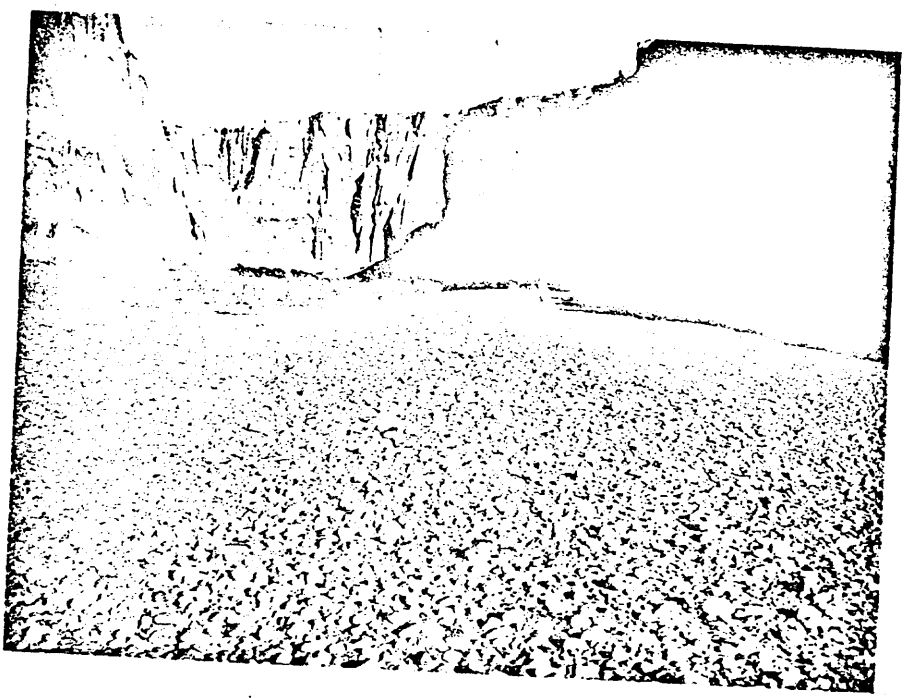


Figure 8 - Colorado River at a major channel control by armoring near Range 20 in October 1966.

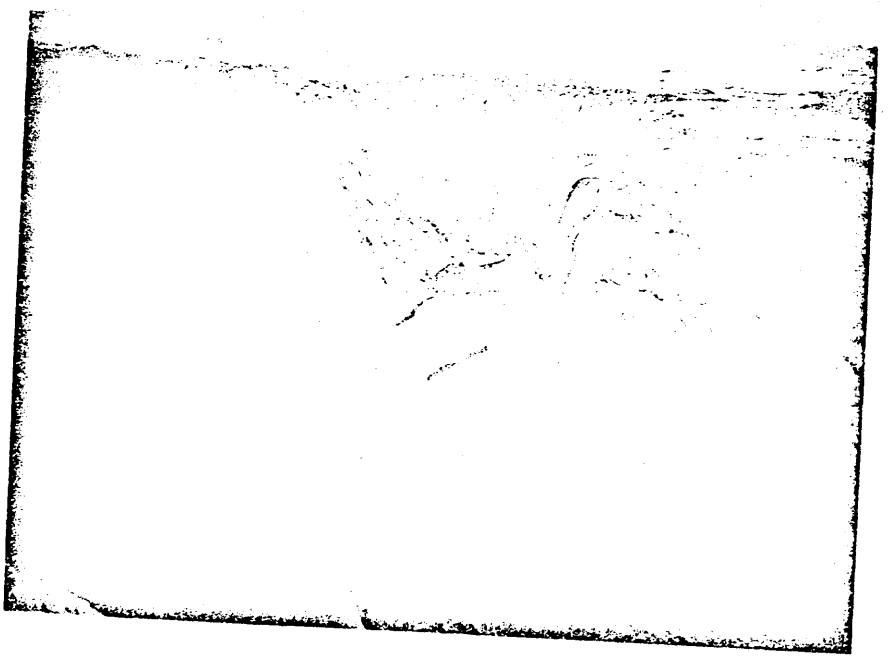


Figure 9 - Colorado River below Glen Canyon Dam showing minor control by armoring near Range 10 in July 1975.

Figure 10 - Gravel-cobble size armoring near Range 15A on Colorado River below Glen Canyon Dam in July 1975.

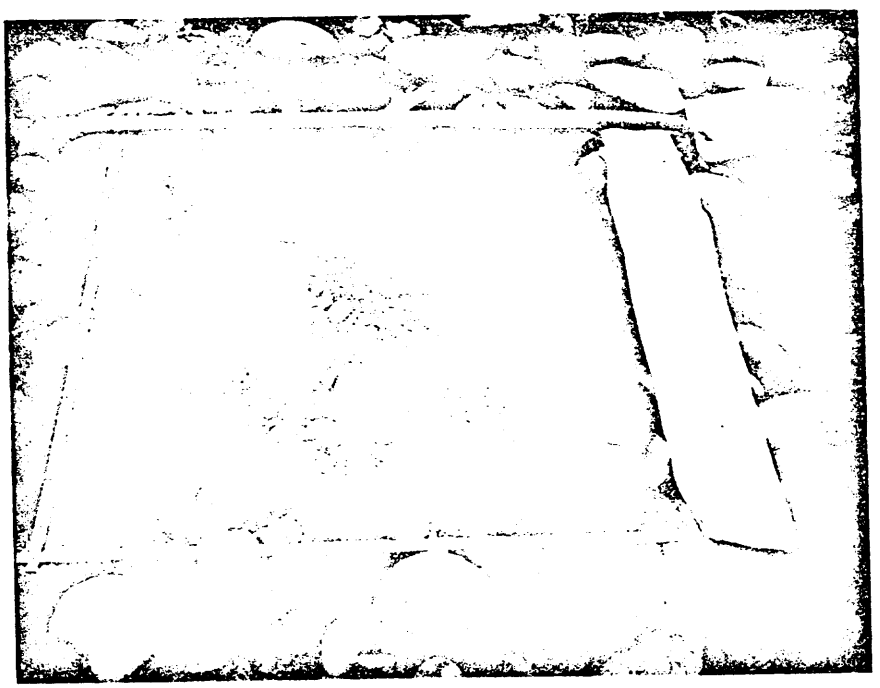


Figure 11 - Material underlying armoring layer near Range 15A on Colorado River below Glen Canyon Dam in July 1975.

(Little and Mayer, 1972) and the Velocity-Xi Adjustment to Einstein's total load transport (Pemberton, 1972) were tested. In this evaluation of armor the critical period for degradation was considered to be from beginning of construction until 1963 as shown on figure 5. The dominant discharge for this period as defined by the maximum mean daily flow hydrograph (figure 5) was assumed to approximate the 2-year flood peak frequency and was 1,840 cubic meters per second (65,000 cubic feet per second). The average channel hydraulics for this discharge together with the size analysis of materials assumed to be available for armor from the underlying gravel deposits in 1956 gave the following armoring sizes:

Armoring Technique	Armoring Size (Millimeters)
Competent Bottom Velocity (High Velocity Range)	76
Meyer-Peter, Muller	23
Schoklitsch	10
Little and Mayer	97*
Einstein Total Load (USBR Velocity-Xi Adjustment)	23

* Geometric mean diameter of armor mixture.

The results tabulated above were supported by the samples of armoring material as indicated by figure 4. The minimum size of armor shown for the 1975 samples is about 40 millimeters, while that shown for 1966 was about 10 millimeters. The geometric mean diameter of armor indicated by Little and Mayer of 97 millimeters is in good agreement with the 1966 and 1975 armoring samples.

CONCLUSIONS

Degradation below Glen Canyon Dam has been controlled by armoring of cobble-size materials with a D_{50} of about 100 millimeters. There are presently about 10 of these gravel-cobble control bars in the 24-kilometer (15-mile) reach of the Colorado River from Glen Canyon Dam to Lees Ferry. The 1957 degradation study indicated that the control below range 15 and Paria Riffle would control extensive degradation. In the approximately 19 years since construction first started on the dam up until 1975, resurveys of ranges have supported most of the conclusions made in the 1957 study. The Paria Riffle, consisting of cobbles and boulders, has not changed appreciably since construction of Glen Canyon Dam.

An accelerated rate of degradation took place immediately below Glen Canyon Dam during the construction period from 1959 to 1963. The cofferdam located above the construction area provided a storage area for sediments, which in

combination with large releases of clearer water, resulted in the accelerated degradation. As anticipated, the degradation that first occurred below the dam has moved downstream. The resurveys of ranges have shown that about 9.87 million cubic meters (8,000 acre-feet) of the bottom sediment have scoured from the channel compared with the predicted value in the 1957 study of 8.26 million cubic meters (6,700 acre-feet). In comparing the 1975 profiles with the 1965 profiles, the channel has become quite stable with very little change in the upstream reaches and with only minor changes, such as the medium and coarser sand-size materials being moved into and through the lower reach of the Colorado River above Lees Ferry.

REFERENCES

Gessel, Clyde D., 1963, Sediment Storage and Measurement in the Upper Colorado River Basin, Proceedings of the Federal Interagency Sedimentation Conference, ARS Misc. Publication No. 970, pp 778-784

Little, W. C., and Mayer, P. G., May 1972, The Role of Sediment Gradation on Channel Armoring, Georgia Institute of Technology

Miller, C. R., and Borland, W. M., 1957, Tail Water and Degradation Studies Colorado River below Glen Canyon Dam, unpublished Bureau of Reclamation study used in designs

Pemberton, Ernest L., 1972, Einstein's Bedload Function Applied to Channel Design and Degradation, Chapter 16 in Sedimentation, Symposium to Honor Professor H. A. Einstein by Hsieh Wen Shen, Colorado State University, 16-1 to 16-28

Strand, Robert I., 1973, Chapter on Sedimentation in Design of Small Dams, Bureau of Reclamation, pp 767-796